Mapping and Ablation of Complex Cardiac Arrhythmia Guided by a Novel Three-Dimensional Non-Contact Endocardial Activation Mapping System

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FUNG ET AL.: ***Mapping and Ablation of Complex Cardiac Arrhythmia Guided by a Novel Three-Dimensional Non-Contact Endocardial Activation Mapping System.*** *Conventional cardiac activation mapping requires a sequentially-based method of positioning a catheter in contact with the endocardium to generate intracardiac electrograms at single points during sustained arrhythmia. Significant limitation of such point by point mapping may be encountered when applying to complex arrhythmia e.g. non-sustained arrhythmia or haemodynamically unstable arrhythmia. A novel non-contact mapping system (Ensite 3000 system) providing a three-dimensional simultaneous display of arrhythmia activation may offer a solution. The non-contact mapping system consists of a specially designed balloon catheter (Ensite EP catheter) with 64 insulated wires over the surface of the balloon for sensing electrical potentials on the endocardium and transmitting the signals to the Patient Interface Unit (PIU) for processing. It uses proprietary algorithms to reconstruct the three-dimensional cardiac chamber geometry and global endocardial activation sequences. This non-contact mapping system can provide a navigational guide in assisting ablation catheter to the target sites of interest. In this article, the mapping and ablation procedures in patents with (1) focal right atrial tachycardia, (2) haemodynamically unstable right ventricular outflow tract ventricular tachycardia and (3) symptomatic ventricular ectopics are described. Using this non-contact mapping system, patients with haemodynamically unstable or symptomatic non-sustained arrhythmia may also be successfully treated by ablative therapy with shorter procedure and fluoroscopy time. (J HK Coll Cardiol 2001;9:157-165)*

Ablation, non-contact three-dimensional mapping

摘要

常規的心臟激動標測需要導管與心內膜相接觸順序性標測，在持續性心律失常過程中形成的內單點心電圖。這種逐點標測在複雜的心律失常如非持續性心律失常或血液動力學不穩定的心律失常時則有其顯著的局限性。一種新的標測系統（Ensite 3000 system）能三維地同步顯示心律失常的激動因而可能提供一種解決方法。這種非接觸性的標測系統由特殊設計的球囊導管（Ensite EP catheter）組成，其表面附有64個絕緣導綫用於手術中感知心內膜電位並將信號傳輸至病人體表裝置（PIU）。應用特殊的算法重構三維的心腔幾何和全心內膜激動順序，這種非接觸標測系統能指導管到達有意義的靶點。本文應用該標測和消融程序對下列病人進行觀察：（1）局竈性的右側房速（2）血液動力學不穩定的右室流出道室速（3）有癥狀的室性異位節律。應用這種非接觸性標測系統，對於血液動力學不穩定的或非持續性的有癥狀的心律失常病人，可能在較短的操作過程及較短暴光時間內得到成功的消融治療。

關鍵詞：消融　　非接觸性三維標測

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Introduction

Detailed catheter-based mapping of cardiac chambers is a prerequisite for successful ablation therapy for cardiac arrhythmia. Current techniques using catheters with a limited number of recording electrodes guided by fluoroscopy have significant limitations for cardiac mapping. It only provides a single-point electrophysiological data under two-dimensional fluoroscopic display. Point by point contact mapping is required during sustained arrhythmia to look for earliest site of activation. The conventional techniques are difficult or perhaps impossible to map non-sustained or haemodynamically unstable arrhythmia. The new non-contact mapping system (Ensite 3000 system, Endocardial Solution Inc) providing a global and simultaneous view of arrhythmia activation may offer a solution to the limitations of conventional mapping techniques.[1-6] The Ensite system consists of a 7.5 ml balloon mounted on a 9 French catheter which is woven of a braid of 64 insulated 0.003 inch diameter wires. This non-contact catheter together with a standard roving catheter are positioned inside the cardiac chamber. By emitting a high frequency signal from the roving catheter, distance between the two catheters can then be calculated. By moving the roving catheters along the endocardial surface and certain anatomical landmarks (e.g. tricuspid annulus, His bundle or inferior vena cava), the geometry of the cardiac chamber can then be established. As the roving catheter moves along the endocardial surface, sampling of several reference intracardiac potential was recorded. These electrical potentials on the endocardium detected by the roving catheter together with the anatomical information are relayed to the Patient Interface Unit (PIU) of the workstation. This workstation then uses proprietary algorithms to combine the electrical and anatomical information of the cardiac chamber of interest. In each cardiac cycle, endocardial potentials sensed by the non-contact catheter were amplified, filtered and sampled at 1200 Hz and passed to a high-order boundary-element computation system. The computation system uses an inverse formulation to solve Laplace's equation for each sample, yielding endocardial potentials of the whole cardiac chamber. The computed electrograms or virtual electrograms derived by the Ensite system have been well validated with negligible difference from those of conventional contact mapping. The potentials are applied to spline curve model of the chamber corresponding to 3360 points over the endocardial surface of the cardiac chamber. The three-dimensional display of the Ensite system provides both anatomical and electrophysiological data for activation mapping. The position of the ablation catheter is marked in this three-dimensional display map. Therefore this system offers a non-fluoroscopic navigational guide to the ablation catheters targeting the sites of interest.

In this article, the application of this novel non-contact mapping system on 3 patients with complex cardiac arrhythmia was described. This global activation mapping may allow a better understanding of the critical elements necessary to initiate and maintain a tachycardia. Moreover, with the use of this new mapping system, the indication for therapeutic application of radiofrequency ablation may be extended to those patients suffering from haemodynamically unstable or non-sustained arrhythmia.

Patients

We studied 3 patients with complex cardiac arrhythmia: (1) focal right atrial tachycardia (AT), (2) haemodynamically unstable right ventricular outflow tract (RVOT) ventricular tachycardia (VT) and (3) symptomatic ventricular ectopics (VE) in arrhythmogenic right ventricular dysplasia (ARVD).

First patient was a 46-year-old lady presented with recurrent palpitation for 3 years. Long RP tachycardia was detected in 24-hour Holter study. On average, she experienced 2 episodes of palpitation attack per week, which lasted for 2-3 hours despite 2 different anti-arrhythmic drugs. Echocardiographic examination before electrophysiology study (EPS) showed normal chamber sizes, heart valves and cardiac function. Second patient was a 59-year-old gentleman presented with recurrent near syncope preceded by fast palpitation. Echocardiographic examination showed normal left and right ventricles. Holter study showed regular wide complex tachycardia with rate of 200/min during his symptoms. Cardiac catheterization and cineangiography showed normal coronary arteries, left and right ventricles. Programmed electrical stimulation (PES) was able to induce clinical arrhythmia of cycle length 250 ms with left bundle branch block (LBBB) pattern and inferior axis by 3 ventricular stimuli suggesting

RVOT VT. His blood pressure dropped to 80/40 mmHg during tachycardia with marked dizziness. Overdrive pacing with cycle length 200 ms was successful in terminating the arrhythmia. There was breakthrough palpitation attack despite antiarrhythmic therapy. The patient preferred ablative therapy for his drug-resistant arrhythmia. Third patient was a 32-year-old lady with symptomatic VE. Frequent VE and non-sustained VT are detected in Holter study with 12% of total QRS complex due to VE. Echocardiographic examination showed slightly enlarged RV and normal LV function. Magnetic resonance imaging confirmed fatty replacement of RV free wall suggestive of arrhythmogenic RV dysplasia. She had no history of syncope. Her VE had LBBB pattern with inferior axis again suggesting RVOT in origin. She was treated by various antiarrhythmic drugs but all failed to control her symptoms. She agreed for ablation therapy.

Methods

All 3 patients gave written consents before the procedures. All antiarrhythmic drugs were stopped for at least 5 half-lives before the procedures. The procedures were performed under local anaesthesia. Standard diagnostic electrophysiological catheters were positioned conventionally in the heart via right femoral vein under fluoroscopic guidance. The Ensite non-contact catheters were positioned inside the selected cardiac chamber via left femoral vein. In the patient with focal right AT, the Ensite catheter was advanced to right atrium (Figure 1) with guide wire lined up from inferior vena cava (IVC) to superior vena cava (SVC). In the patient with right ventricular outflow tract ventricular tachycardia and symptomatic ventricular ectopics, the Ensite catheter was positioned in the RVOT (Figure 2) with guide wire lined up from RVOT to pulmonary artery across pulmonary valve (PV). Intravenous heparin was given to maintain activation clotting time between 300-400 seconds throughout the procedure in a half-hour blood-sampling interval.

Creation of Chamber Geometry and Isopotential Map Generation

To create chamber geometry and generate the isopotential map, the non-contact Ensite catheter and a standard roving catheter were positioned in the cardiac chamber of interest. A 5.68 kHz (range of audible frequency: 0.02-20 kHz) signal was emitted from the

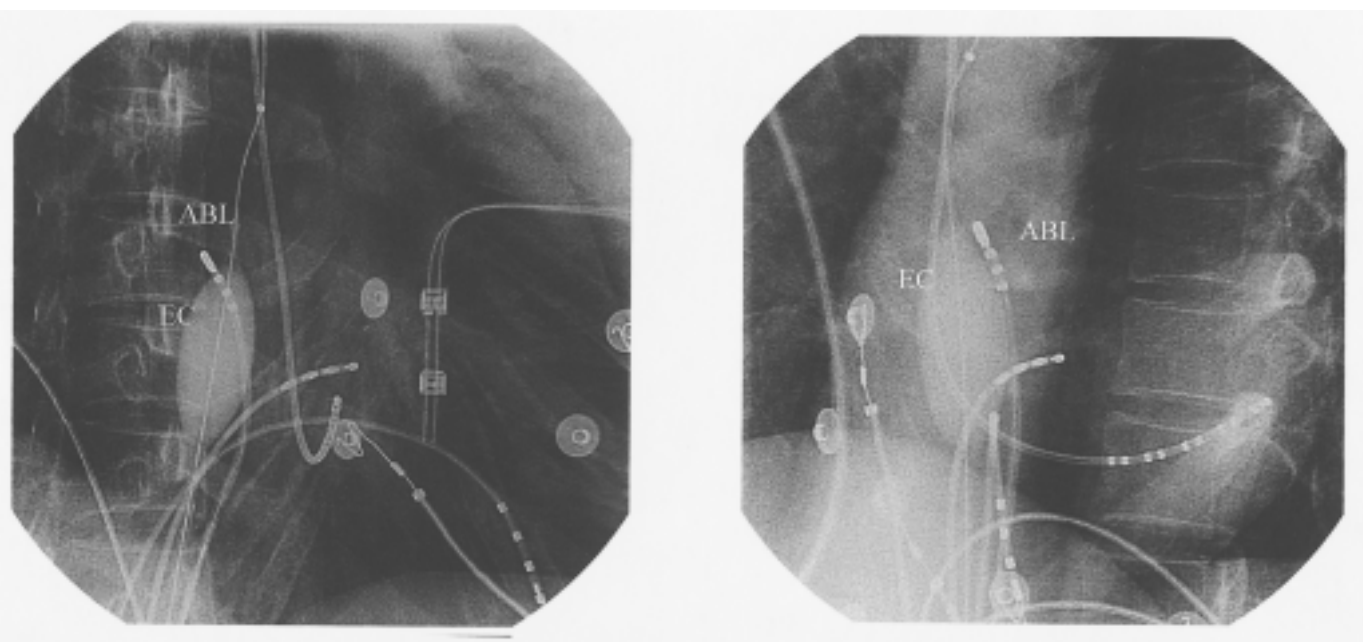

Figure 1. *Left Panel. Right Anterior Oblique View. Right Panel. Left Anterior Oblique View. X-rays of patient with focal right atrial tachycardia with Ensite Catheter (EC) in-situ. ABL=Ablation catheter.*

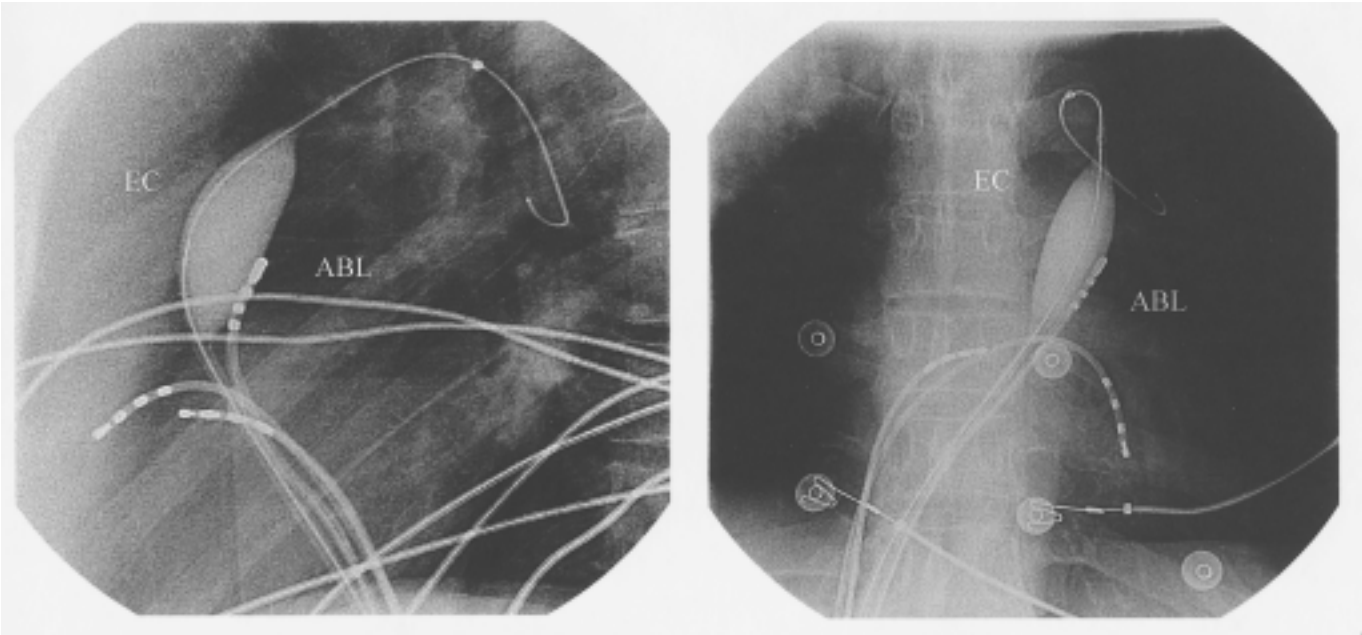

Figure 2. *Right Panel. Anteroposterior view, and Left Panel. Lateral view. X-rays of the patient with ARVD and symptomatic ventricular ectopics with Ensite Catheter (EC) in-situ. ABL=ablation catheter.*

electrode tip of the roving catheter that was in contact with the endocardial surface. Good contact of the roving catheter to the endocardial surface was confirmed by bipolar intracardiac signal detected by the roving catheter. By manipulating the roving catheter along the endocardial surface of the chamber, the strength of the signal was continuously recorded at each of the 64 array electrodes over the Ensite catheter. Data are sampled at 1.2 kHz and filtered with a programmable bandwidth between 0.1 and 300 Hz. From these recorded potentials, the electrophysiological data of the roving catheter in relation to the Ensite catheter could be computed by the boundary element method. This method (Appendix I) uses an inverse formulation to solve Laplace's equation for each sample, yielding endocardial potentials or virtual electrograms and thus creating the isopotential map of the chamber. With this method, location of the roving catheter tip in relation to the Ensite catheter can also be computed. Sampling of the location of the roving catheter occurred at the diastolic phase of cardiac cycle. The system automatically stores only the most distant points visited by the roving catheter in order to ignore those detected when the catheter is not in contact with the endocardial wall. With all the sampled locations, the chamber geometry could then be established. The sampled locations were put into a convex hull algorithm to build a faceted model. Using a bicubic-spline smoothing algorithm, the convex model is converted into a high-resolution contoured model of the chamber. By combining the location and endocardial potential data, the patient-specific electroanatomic information of the cardiac chamber could be displayed. With advanced computer graphics, the chamber model could be rotated in any projection to facilitate understanding of activation sequences. The isopotential mapping was displayed in a colour-coded format. After completing the chamber geometry and isopotential map, the roving catheter could be removed from the chamber. While the Ensite non-contact catheter is in the fixed position inside the cardiac chamber, the changes of endocardial potential by activation sequences during arrhythmia could be recorded for analysis.

Arrhythmia Identification and Ablation Navigation

With induction of clinical arrhythmia, the activation of the arrhythmia could be displayed in the three-dimensional contour of the cardiac chamber. Full chamber vision allowed us to rapidly elucidate the characteristics of the arrhythmia e.g. reentrant circuit,

focal tachycardia or common pathway and exit points. Moreover, by means of locator property of the standard roving catheter, the system would offer a navigational guide to the ablation catheter to area of interest.

Results

Successful end-point of the procedure was defined as non-inducibility of clinical arrhythmia with and without isoproterenol. The procedures were successful in all three patients. The procedure time varied from 2.5 to 5.0 hours. The mean time in establishing chamber geometry was 15.0 minutes. Fluoroscopy time varied from 12.6 to 35.0 minutes. No complication was encountered.

Patient with Focal Right Atrial Tachycardia

EPS showed no VA conduction. Programmed electrical stimulation (PES) was unable to induce clinical arrhythmia. With isoproterenol infusion, frequent supraventricular ectopics were noted with right atrial signal earlier than that of coronary sinus suggesting right atrial ectopic beats. Atrial burst pacing with cycle length 320 ms was able to induce sustained arrhythmia of cycle length 360 ms with earliest atrial activation at high right atrium. Injection of ATP to induce AV block failed to terminate the atrial arrhythmia. Mapping of the sinus beat versus supraventricular ectopics confirmed earliest activation of the ectopic beat originated from posterior wall of right atrium. With initiation of arrhythmia, the earliest site of activation was identified at the same spot as the ectopic beat suggesting focal nature of the clinical arrhythmia. The sequence of atrial activation during focal atrial tachycardia was depicted in Figure 3 with a 10 ms time frame. No reentry circuit was detected during the atrial tachycardia. The total atrial activation time was 80 ms which was much shorter than the tachycardia cycle length. Radiofrequency (RF) energy was delivered

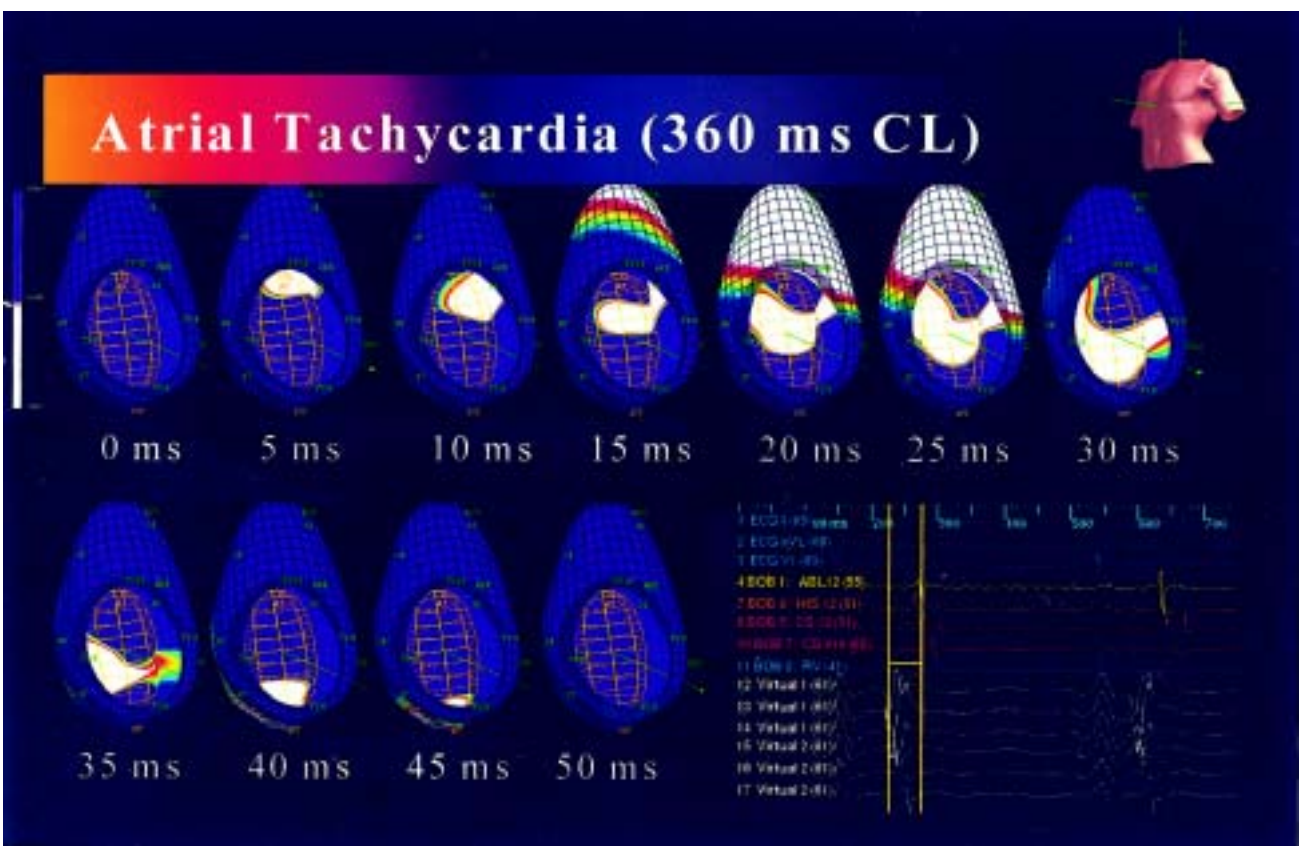

Figure 3. *Activation sequences of the patient with focal right atrial tachycardia in LAO projection. White patch denoted the depolarization wavefront from 0 to 50 ms.*

to the right atrial focus during tachycardia. Tachycardia was terminated and sinus rhythm resumed 5 seconds after the onset of RF application. Total number of RF ablation was two. The atrial tachycardia was not inducible by burst pacing or PES with and without isoproterenol infusion. At 2-month follow up, the patient had no recurrence of atrial arrhythmia.

Patient with Haemodynamically Unstable RVOT VT

With positioning of Ensite catheter to RVOT, geometry of RVOT was established with location of pulmonary valves, His bundle, RV apex and tricuspid annulus. VT was induced again by PES with concurrent non-contact activation mapping. Significant haemodynamic compromise was again detected and required emergency termination of arrhythmia by overdrive pacing. Activation mapping information during the period of VT was recorded for off-line analysis. Earliest focus of activation during VT was located and marked at lateral wall of RVOT below PV, as shown in the three-dimensional display in Figure 4. With the Ensite navigational guide, roving catheter was manipulated to the earliest focus as marked in the three-dimensional display. RF energy was delivered via the roving catheter to the target focus during sinus rhythm. The total number of RF ablation was five. PES and burst pacing was unable to induce VT with and without isoproterenol infusion after ablation. Antiarrhythmic drugs were stopped and there was no recurrence of VT at 2-month after the procedure.

Patient with Symptomatic Ventricular Ectopics

The Ensite catheter was positioned to the RVOT (Figure 2) as in the last patient. There was no sustained VT inducible by PES with and without isoproterenol.

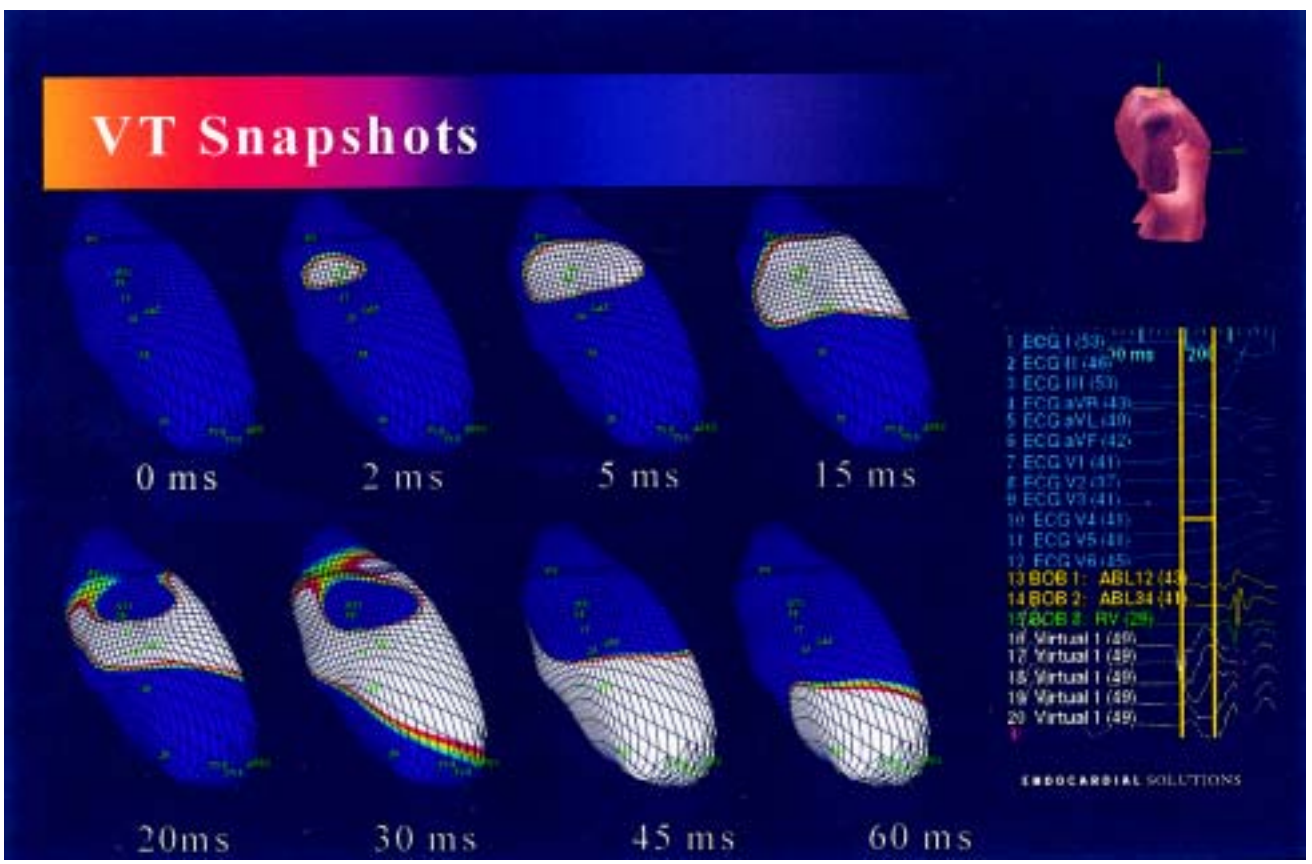

Figure 4. *Activation sequences of the patient with RVOT VT in lateral projection. White patch denotes the depolarization wavefront from 0 to 60 ms. The earliest site of activation was located at lateral wall of RVOT just below the pulmonary valve (the dark continuous line at top part of the RVOT model). Radiofrequency ablation was delivered to the white patch area shown in the 2 ms time frame.*

Frequent VE was noted. Non-contact mapping of the VE showed the earliest site of activation of these VE come from posterolateral wall of RVOT below the PV. RF energy was delivered to the focus of earliest activation of the VE. Multiple RF ablations around the focus were required to suppress VE. The total number of RF ablations was 12. PES and pacing with and without isoproterenol failed to induce VE or non-sustained VT. Repeated Holter study showed marked reduction of VE to less than 1% of total QRS complexes and marked symptomatic improvement as reported by patient after RF ablation.

Discussion

These three cases well illustrated that the non-contact endocardial activation mapping system could greatly enhance the understanding of arrhythmia activation and facilitate mapping in patients with haemodynamically unstable or non-sustained arrhythmia. Conventional activation mapping in patients with atrial tachycardia is a prolonged procedure with significant fluoroscopic exposure. In our patient, the actual time spent between initiation and termination of arrhythmia by RFA was less than 1 hour reflecting the effectiveness of the mapping system and the navigational guide in positioning the ablation catheter. Moreover, in patient with haemodynamically unstable VT, activation mapping by conventional method would be almost impossible. The Ensite system provided a record-and-review off-line analysis of the activation mapping during the few beats of unstable VT. This unique feature enables one to apply activation mapping in ablation of VT in ischaemic heart disease. Single beat mapping with the Ensite system permits short-duration but high-resolution mapping of the ectopic beat, as illustrated in the last patient. With regards to using ablative therapy for symptomatic ventricular ectopics in the third patient, it has to be emphasized that this is not a first line standard therapy for this condition. Lee et al. reported that ablation for symptomatic frequent VE was associated with high rate of cure and improvement in the quality of life and appeared superior to drug therapy.[11-12] Two antiarrhythmic drugs had been tried but both failed to control her symptoms. Therefore, such non-conventional ablative therapy was suggested and accepted by the patient. The apparently higher number of RF applications in the last patient may be related to the diseased and fibrotic tissue in the affected right ventricle. Whether it is related to the accuracy of the mapping system requires further research and mapping experience in patients with ARVD, especially comparing to conventional catheter-based methods. However, the non-contact mapping should not be considered as a substitute for the conventional methods. The three cases discussed could well be managed by conventional methods. Whether the postulated benefit of shorter procedure time, less fluoroscopic exposure and guiding ablation for non-sustained or unstable arrhythmia by the non-contact system requires randomized comparison with the conventional methods in the future.

Comparison of the Ensite System with other Catheter-Based Mapping System

Conventionally increasing the number of electrodes to a single contact catheter or putting multiple catheters inside the chamber of interest for activation mapping had been advocated but with obvious limitations. Even using catheters with different shapes, the entire endocardial surface activation could not be analyzed simultaneously.[7,8] Moreover, the multiple catheters may hinder the positioning of ablation catheter to the specific site of interest.

Pace mapping may be an alternative mapping method for unstable arrhythmia. By positioning a catheter at a specific point, pacing via the catheter tip to acquire 12-lead matched ECG to look for focus of interest has been used to map unstable VT. However, identical pace maps can be observed up to 8 mm from a tachycardia focus.[9] Precision of pace mapping is a limitation.

With a special catheter containing a magnetic field sensor along with a magnetic field emitter located beneath the patient table (CARTO system), Gepstein et al. created a three-dimensional electroanatomical mapping of a cardiac chamber.[10] However, this system requires serial mapping of endocardial sites with a contact catheter. Therefore, this system may not be useful for mapping VT associated with haemodynamic instability.

Limitation of the Ensite System

There are 3 major limitations of the Ensite System. In vitro testing, the accuracy of computed

electrograms deteriorated significantly when the distance between the array to the endocardial surface is more than 50 mm, thus creating difficulty in mapping of severely enlarged chamber or remote site from the catheter.[3] Second limitation is in patients with ischaemic VT utilizing epicardium as part of the circuit. As the system has assumed endocardial surface depolarization, epicardial reentry circuit may not be clearly delineated by such mapping system.[5] This non-contact mapping system assumed that the geometry of the chamber had no significant difference between during sinus rhythm and tachycardia. In vigorously contracting chamber during tachycardia, theoretically, the geometry of the chamber may be distorted and affect the accuracy of the computed geometry. However, the relatively high success rate of ablative therapy using this mapping system may indicate that this theoretical error may actually be negligible.[5] One of the major concerns of using this system is the cost, especially comparing to conventional methods. To our knowledge, there is no data regarding cost-effective analysis of this system comparing to conventional method. However, when performing the analysis, factors like procedure time, fluoroscopic exposure and application of the system in selected patients with haemodynamically significant or non-sustained arrhythmia should be taken into account.

Conclusion

Our data support the early experience with the non-contact endocardial activation mapping system in guiding successful ablation. Better understanding of arrhythmia substrate can also be provided by this mapping system. The application of this mapping technique may enable one to tackle non-sustained arrhythmia or complex arrhythmia associated with haemodynamic instability.

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Appendix I

The electrical activity detected by the electrodes on the surface of the Ensite catheter is generated by the potential field on the endocardial surface. Cavitary electrograms detected by the non-contact electrodes are of lower amplitude and frequency than the source potentials on the endocardium, which limits their clinical utility. A technique to enhance and resolve the actual endocardial surface potentials has been devised on an inverse solution to Laplace's equation using a boundary element method, yielding endocardial potentials or virtual electrograms.

The potential distribution on the Ensite catheter created by endocardial activation is described by Laplace's equation. The potential field at any one electrode is influenced by the potentials from the entire endocardium, with the degree of influence diminishing with the distance between the electrode and each endocardial point. With this information, it is possible to compute endocardial electrograms from the potentials detected on the Ensite catheter surface by an inverse solution of Laplace's equation.

This inverse solution is based on following formula:

$$\iint_{\vartheta D} \{ v\,\vartheta w/\vartheta n - w\,\vartheta v/\vartheta n \} dA = \iiint_{D} \{ v\,\nabla^2 w - w\,\nabla^2 v \} dD$$

where D is a domain (the blood pool), ϑD is the boundary of D (the endocardium plus the Ensite balloon), $\vartheta/\vartheta n$ represents the outward normal on D, ∇^2 is the Laplacian, dA is the surface area differential and dD is the volume differential, w is the potential field created by a unit charge in free space, and v is the potential field in the domain. This equation is using the boundary element method, which is a numerical approach to solving integral equations such as those governing the behaviour of electric fields in volume conductors.